SUBCONTRACT NP-1

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Westinghouse Astronuclear Laboratory

XE-PRIME XENON MEASUREMENTS

CHAPTER E

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CHAPTER E.
XE-PRIME TEST ANALYSIS REPORT

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E. XENON MEASUREMENTS

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1. Introduction

The ability to restart a nuclear reactor at some time following powered operation is dependent in part on the reactivity worth of the fission product inventory at the time of restart. Since it may be necessary to provide a reactor design capable of restart under certain adverse conditions resulting from fission product effects, it is important to know the magnitude of the reactivity effect that can be expected. With this goal then, the objective of the tests described in this chapter was to determine experimentally the reactivity effect of the fission product inventory as it varied during the shutdown period following a power test. The tests were conducted in EP-5C (6/11/69) and EP-4A (6/26/69) in an attempt to map the fission product reactivity worth from the power test performed in EP-5C.

In the sections that follow, the expected reactivity effect of Xenon-135 and the measured fission product reactivity effects are presented. These are compared in Section 4. The applicability to NERVA is discussed in Section 5.

2. Expected Xenon Worth

In a nuclear reactor, even after a brief period of high power operation, the reactivity effect due to some fission products may be significant. Fission products cause parasitic absorption, which may result in a significant negative reactivity effect if those products have both a very large absorption cross section and/or a large total fission yield. The most serious poison of this type is xenon-135, which has an absorption cross section for 2200 meter per second neutrons of 3.6×10^6 barns[1] (the largest known absorption cross section of any isotope) and a direct fission yield of 0.237 percent. The mass-135 fission product chain has a total fission yield of 6.41 percent, one of the largest known yields.

Xenon-135 is produced in two ways from the fissioning of uranium-235. It is formed directly as a fission fragment and indirectly as a member of the mass-135 fission product chain, in which it is the daughter of iodine-135. Table E-1 gives the nuclear constants for the mass-135 fission product chain. Since the half lives of antimony-135 and tellurium-135[2] are very short compared to that of iodine-135, it has been assumed that iodine-135 is formed directly with a fission yield of 0.0617.

The differential equations which represent the iodine-135 and xenon-135 concentrations at a point in the reactor are:

$$\frac{dI}{dt} = \gamma_I R_f - \lambda_I I$$

$$\frac{dX}{dt} = \gamma_X R_f + \lambda_I I - \lambda_X X - X \int_E^x \phi \, \sigma_a \, dE$$

where,

I = concentration of iodine-135, atoms per cc

X = concentration of xenon-135, atoms per cc

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[1] BNL-325, Second Edition, Supplement No. 2, "Neutron Cross Sections," Volume II, Brookhaven National Laboratory, May 1966.

[2] These are precursors in the decay chain. See Table E-1

γ_I = fission yield of iodine-135, including precursors = 0.0617

γ_X = direct fission yield of xenon-135 = 0.00237

λ_I = decay constant of iodine-135 = 2.874×10^{-5} per sec

λ_X = decay constant of xenon-135 = 2.106×10^{-5} per sec

R_f = total fission rate, fissions/cm^3-sec

$\int_E \phi \sigma_a^x dE$ = burnup rate of xenon-135, atoms per sec.

Assuming that no iodine-135 or xenon-135 is present in the reactor at the start of the full power run ($t = 0$), the iodine-135 and xenon-135 concentrations at any time during a run at constant power are given by the solution of the above two differential equations. This solution is presented in detail in APPENDIX H to the "NRX-A6 Test Analysis Report"* and will not be repeated here.

After shutdown of a nuclear reactor, the iodine-135 inventory decays to xenon-135 and the xenon-135 concentration initially increases since the iodine-135 half-life is shorter than that for xenon-135. The xenon-135 concentration reaches a maximum about 11 hours after shutdown. The iodine-135 and xenon-135 concentrations following shutdown are given respectively by the equations:

$$I = I_s \exp(-\lambda_I T)$$

$$X = X_s \exp(-\lambda_x T) + \frac{\lambda_I}{\lambda_I - \lambda_x} I_s \left[\exp(-\lambda_x T) - \exp(-\lambda_I T)\right]$$

where,

I_s = concentration of iodine-135 at the end of the full power run, atoms per cc

X_s = concentration of xenon-135 at the end of the full power run, atoms per cc

* WANL-TNR-223, "NRX-A6 Reactor Test Analysis Report," 8/68.

T = time since the end of the full power run, seconds.

The time of maximum xenon-135 concentration (after the end of the full power run) is given by the expression:

$$T_{max} = \frac{1}{\lambda_x - \lambda_I} \ln\left[\frac{\lambda_x}{\lambda_I}\left(1 + \frac{(\lambda_I - \lambda_x)}{\lambda_i}\frac{X_s}{I_s}\right)\right] .$$

The radial distribution of the xenon-135 in the core at the time of shutdown is nonuniform because of the variation in burnup rate across the core. However, the xenon-135 produced from the decay of iodine-135 has a uniform radial distribution, since the parent iodine-135 has nearly a uniform radial distribution during the power run. Since iodine-135 has a small absorption cross section, it has no significant burnup and is distributed as the fission density After shutdown the additional xenon-135 produced by iodine-135 decay soon predominates, so that the radial xenon-135 distribution becomes more uniform.

Figure E-1 shows the expected xenon-135 reactivity worth in the XE-Prime reactor as a function of time after the end of the EP-5C full power run. As noted above, the maximum xenon-135 concentration was expected about 11 hours after shutdown. The above analysis has assumed that during EP-5C essentially no mass-135 fission products diffused out of the XE-Prime core. This is consistent with results reported by the WANL Physical Sciences Laboratory for the NRX-A6 reactor which show about a 3 percent diffusion of mass-135 fission products at design conditions.*

Figure E-1 has been developed from the detailed NRX-A6 calculations referenced above by revision of Figure H-3 in the NRX-A6 Test Analysis Report for the differences in integrated full power time between NRX-A6 (EP-111A) and XE-Prime (EP-5C). The magnitude of the quantity I_s in the above equations is the significant factor and this varies as

* J. Roesmer, Physical Sciences Laboratory, WANL, personal communication.

1-exp ($\lambda_1 t_s$) where t_s is the time covered by the test. For NRX-A6, EP-IIIA, with nominally 3600 seconds of operation at full power, this expression has the value 0.0983. For XE-Prime's EP-5C, with an integrated power-time of 118 MW-hr* or an equivalent full power time of about 379 seconds, the expression has the value 0.0108. Thus, the Xenon worth following EP-5C was expected to be about 0.0108/0.0983 times the effect calculated for NRX-A6 or about 11 percent of that presented in the NRX-A6 test analysis report. For ease of comparison with experimental data, the results are shown in Figure E-1 in terms of change in drum bank position from the "clean" (fission product free) condition.

*EP-5C SPEAR Report (Summary, Page 2).

3. MEASURED XENON WORTH

The five criticality measurements related to the fission product (Xenon)* worth determination were made on three days. The first two were made at 2.8 and 7.3 hours after the EP-5C power test was completed The next two were made at 22.8 and 30.2 hours after the power test on the following day. The last measurement was made in EP-4A, about 15 days later, to establish the critical position in the essentially clean--fission product free--condition.

The average drum position and temperature of the major reactor components during these measurements is summarized in Table E-2. An example of the use of this data in the development of a correction to the measured drum position is shown in Table E-3. All temperature corrections in Table E-3 are made relative to the EP-4A conditions. The low range temperature correlation presented in Section F.1 is used for the computation of these corrections. The two temperature corrected drum positions (third entry from the bottom) are then used along with the power level at which the two measurements were made (next to last column in Table E-4) to find a single "Power Corrected Drum Position" that represents the best estimate of the critical position at the time of the measurement. This determination is done in Figure E-2 for the example in Table E-3. Table E-4 summarizes the results of a similar analysis for each of the four fission product (Xenon) worth measurements. Assuming that by EP-4A (15 days after EP-5C) the fission product inventory was negligible, the reactivity effect attributable to Xenon is obtained simply by subtraction of the EP-4A critical position from those shown in Table E-4. These values are compared to the calculated values in Figure E-1.

* The measurements show the effect of all fission products. Calculations have shown that only Xenon will be significant here.

4. CONCLUSION

The comparison between the measured and calculated reactivity effect of Xenon is shown in Figure E-1. The difference between calculation and measurement is considered average agreement and does, seemingly, verify the analytical model on which the expected worth was based. While no estimate of the uncertainty in the measurement is given, note that corrections shown in Table E-4 to the measured values are substantial. The average correction, in fact, is about 1.2 degrees. Comparing this to the average effect measured, 1.7 degrees, indicates that the observed difference between calculation and measurement could, indeed, be considerably larger.

5. APPLICATION TO NERVA

The application of this data to the NERVA development effort is ultimately in the area of reflector design. An accurate analytical model for the Xenon effect permits the development of a reactor design with sufficient drum span to perform the planned mission. That is, reactor restart capability will be assured for each of the burns in the planned mission(s). The data presented in this chapter will aid in the calculation of the Xenon effect and will permit the NERVA drum span/reflector design requirements for mission performance (with regard to the need to Xenon override) to be identified with confidence.

TABLE E-1

(U) NUCLEAR CONSTANTS FOR MASS-135 FISSION PRODUCT CHAIN[1]

Nuclide	Direct Fission Yield	Half-Life
Antimony-135	} 0.0335	1.9 seconds
Tellurium-135		11.2 seconds
Iodine-135	0.0282	6.7 hours
Xenon-135[2]	0.00237	9.14 hours
Cesium-135	--	2.0×10^6 years
Barium-135	--	Stable

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(1) A. DeLucchi, U.S. Naval Radiological Defense Laboratory, personal communication.

(2) An isomer of xenon-135 is also a member of the mass-135 fission product chain, but it has been assumed in this analysis that the ground-state nuclide of xenon-135 is produced directly since the half life of the isomer (15.3 minutes) is much shorter than that for the ground-state nuclide.

TABLE E-2

MEASURED EP-5C CONTROL DRUM BANK POSITION AND TEMPERATURE CONDITIONS

Time After Scram, hours	Range Time Interval, seconds	Control Drum Bank Position, degrees	Average Component Temperatures, °R		
			Core	Reflector	rrel
2.8	49285 - 95	93.71	555	517	528
	49561 - 71	95.20	598	521	539
7.3	65330 - 40	92.90	512	511	509
	65630 - 40	94.18	531	511	515
22.8	35050 - 60	92.40	490	493	493
	35370 - 80	92.85	502	498	499
30.2	61670 - 80	92.83	526	525	513
	62010 - 20	92.95	525	515	512
360 (EP-4A)	45570 - 80	92.90	555	554	555

TABLE E-3

CORRECTIONS TO MEASURED DRUM POSITIONS AT 2.8 HOURS AFTER SHUTDOWN

Experimental Plan	4A	5C	5C
Range Time	45570 - 80	49285 - 95	49561 - 71
Measured Drum Position, degrees	92.90	93.71	95.20
Component Temperatures, °R			
Core	555	555	598
Reflector	554	517	521
Barrel	555	528	539
*Drum Position Corrections, degrees			
Core	---	0	-1.070
Reflector	---	+0.428	+0.381
Barrel	---	-0.147	-0.087
Net	---	+0.281	-0.776
Corrected Drum Position, degrees	---	93.99	94.42
Power Corrected Drum Position (from Figure E-2), degrees	---	94.48	
Change in Critical Angle Relative to EP-4A "Clean" Condition (Plotted in Figure E-1), degrees		+ 1.58	

* Using drum angle coefficients developed in Section 1 of Chapter F, these corrections were computed relative to the EP-4A conditions shown.

TABLE E-4

SUMMARY OF CORRECTIONS TO MEASURED DRUM POSITIONS

Time After Scram, hours	Range Time Interval, seconds	Measured Control Drum Position, degrees	Correction to EP-4A Conditions, degrees	Temperature Corrected Control Drum Position, degrees	Critical to Source Power Ratio (Reciprocal x 10^3)	Power Corrected Drum Position, degrees
2.8	49285 - 95	93.71	+0.28	93.99	112(8.9)	94.48
	49561 - 71	95.20	-0.78	94.42	865(1.1)	
7.3	65330 - 40	92.90	+1.41	94.31	106(9.4)	95.20
	65630 - 40	94.18	+0.93	95.11	1060(0.94)	
22.8	35050 - 60	92.40	+2.15	94.55	>1000(1)	94.60
	35370 - 80	92.85	+1.79	94.64	>1000(1)	
30.2	61670 - 80	92.83	+0.89	93.72	2000(0.5)	94.10
	62010 - 20	92.95	+1.03	93.98	20000(0.05)	

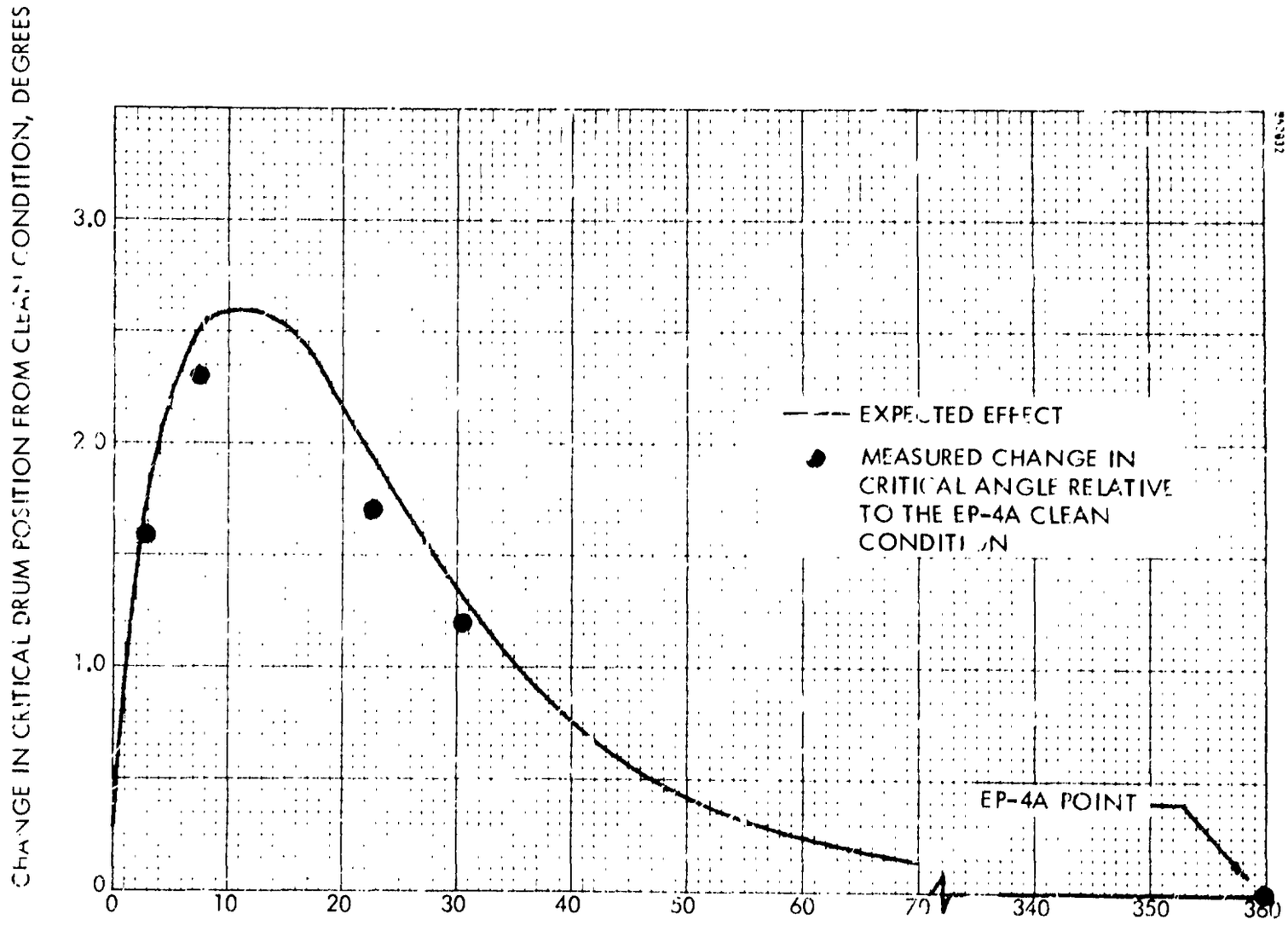

FIGURE E-1 COMPARISON OF CALCULATED AND MEASURED XENON-135 EFFECT

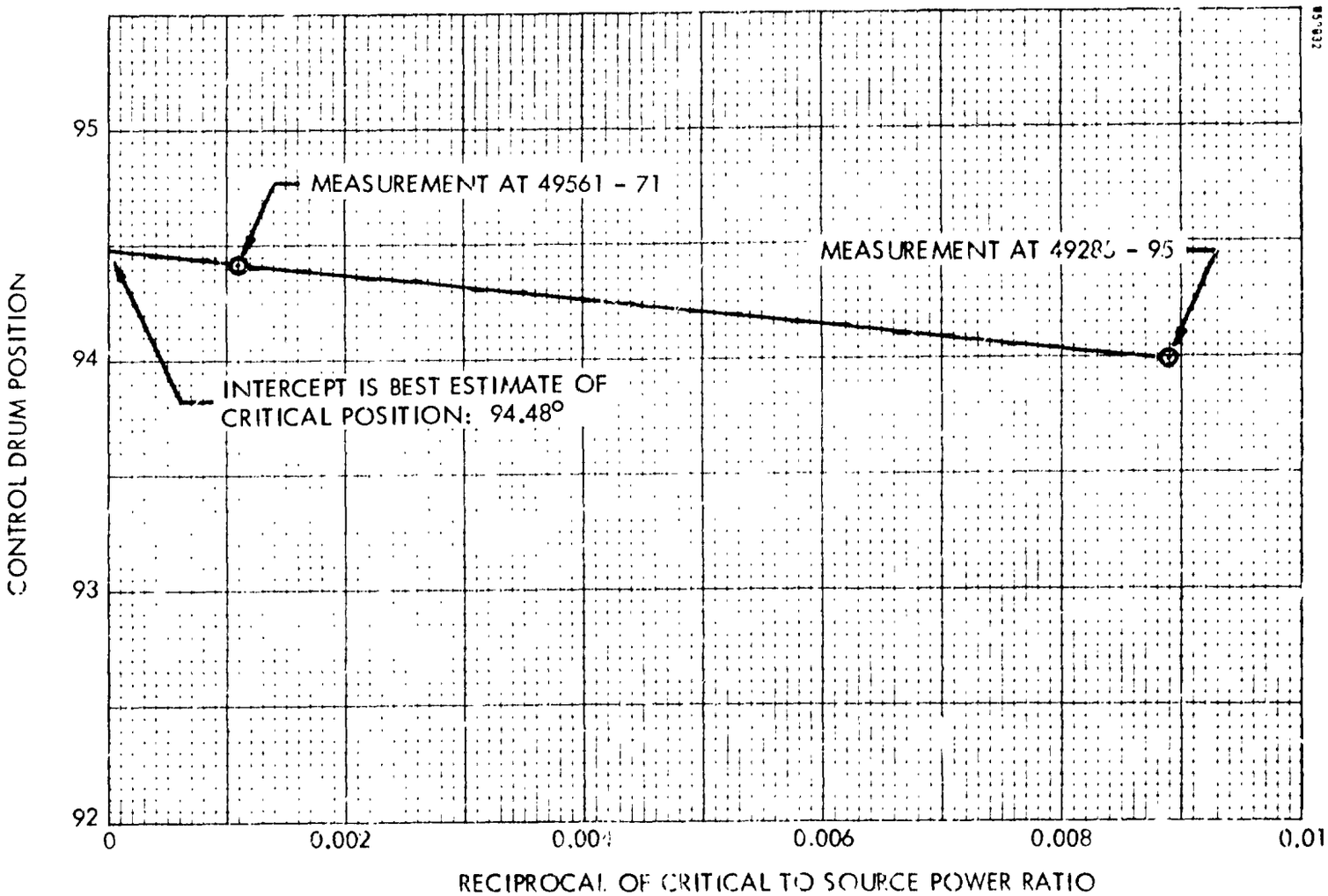

FIGURE E-2 TYPICAL POWER CORRECTION FOR CRITICALITY DETERMINATION (2.8-HOUR XENON MEASUREMENT)